Orchard Worker Localisation Relative to a Vehicle Using Radio Ranging and Trilateration

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Abstract. Safe navigation of labour-aiding robots in commercial orchards will rely on accurate and continuous worker localisation. In this work, an ultra-wideband radio-based system localises a worker via trilateration of four range measurements between antennas on a vehicle and an antenna carried on the worker's belt. Performance results are presented from measurements inside 'work zones' around the vehicle, in open space and in an orchard. At walking speed in open space, when body placement allowed full line-of-sight (LOS) between belt and vehicle antennas, position estimate availability was 99.7% and the distance root mean square error (DRMS) was 57.9 cm. Completely blocked LOS resulted in signal outages and unacceptable performance (11.1% availability; 819.7 cm DRMS). In the orchard, full-LOS performance was similar to that in open-space: 99.3% availability and 63.4 cm DRMS error bound. Orchard trees enabled multipath signal propagation, so blocked-LOS performance was far better than in open-space (60.2% availability; 123.6 cm DRMS). Antenna motion effects were studied in open-space and orchard experiments without body interference. Motion introduced non-collocation errors (individual ranges measured at slightly different positions); DRMS error in open space and orchard were 1.6 and 2.2 times larger than respective static errors. In all experiments the 95th percentiles of the errors were almost twice as large as the DRMS errors. Sporadic large errors and signal outages could be addressed by two belt antennas and filtering. The results indicate that radio ranging offers a practicable approach to orchard worker localisation relative to a nearby vehicle operating at slow walking speeds.

Keywords. Robots; safety; positioning; trilateration; radio sensor.

28 Nomenclature

29	ABSE _x :	Mean absolute error parallel to vehicle frame x-axis.
30	ABSE _y :	Mean absolute error parallel to vehicle frame y-axis.
31	B_i :	i th vehicle radio beacon ($i=1, 2, 3, 4$).
32	B_m :	Mobile radio beacon.
33	d_i :	True distance between B_i and B_m .
34	DRMS:	Horizontal distance root mean square position estimation error.
35	e_x :	Position estimation error parallel to vehicle frame x-axis.
36	e_y :	Position estimation error parallel to vehicle frame y-axis.
37	e_{xy} :	Horizontal position estimation error.
38	GPS _v :	Real time kinematic (RTK) GPS on vehicle.
39	GPS _m :	Real time kinematic (RTK) GPS mobile; carried with mobile radio.
40	LOS:	Line of sight.
41	$O_v(x_v, y_v, z_v)$:	Vehicle coordinate system.
42	$O_g(x_g, y_g, z_g)$:	GPS _v coordinate system.
43	$O_{ts}(x_{ts}, y_{ts}, z_{ts})$:	Total Station coordinate system.
44	$^G P$:	GPS _v coordinates in world frame.
45	$^T P$:	Position expressed in TS frame.
46	$^v P_G$:	GPS _v coordinates expressed in vehicle O_v frame.
47	v_R :	Rotation matrix from O_g to O_v frame.
48	v_T :	Rotation matrix from O_{ts} to O_v frame.
49	$^v P_T$:	Position measured by TS, expressed in vehicle O_v frame.
50	R95:	Radius of a circle centered at the true position, containing the position
51		estimate with probability of 95%.
52	r_i :	Measured range between B_i and B_m .
53	t_i :	Time stamp of measurement r_i .
54	TS:	Total station.
55	$\text{var}(x_r)$:	Asymptotic variance of the non-linear least-squares estimator of x_r .
56	$\text{var}(y_r)$:	Asymptotic variance of the non-linear least-squares estimator of y_r .
57	(x_r, y_r, z_r) :	Estimated position of mobile beacon's antenna via trilateration.
58	(x_i, y_i, z_i) :	i th vehicle beacon antenna coordinates.

59	(x_m, y_m, z_m) :	Mobile beacon antenna coordinates.
60	ε_i :	Range measurement error in r_i .
61	σ^2 :	Variance of the range error, ε_i .
62		

63 **1. Introduction**

64 Orchard operations like spraying, pruning, thinning, mowing, and especially harvesting require
65 intensive manual labour, which contributes significantly to fruit production cost. For example, manual
66 harvesting for apples and sweet cherries accounts for approximately 30% and 50% of production costs
67 respectively (Bull, 2011). Meanwhile, labour availability has decreased in recent years (Hertz and
68 Zahniser, 2013). The combination of high labour cost and labour shortage is a key driver towards the
69 development and adoption of automation technologies that increase the productivity of orchard
70 operations. Towards this goal, researchers have demonstrated that properly designed automated
71 tractors, utility vehicles and labour aids can achieve productivity improvements that range from 20%
72 up to 58% (Moorehead et al., 2012; Bergerman et al., 2012; Ye, et al., 2013). Worker health risks,
73 such as exposure to chemicals or ladder-related accidents can also be reduced. Research on
74 autonomous vehicles for orchard operations has focused on problems like path planning (e.g., Linker
75 and Blass, 2008; Bochtis et al., 2015) and navigation (e.g., Zhang et al., 1999; Barawid et al., 2007).
76 Less attention has been paid to autonomous operation in close proximity with humans, something that
77 is necessary for the anticipated labour efficiency benefits to be achieved in a safe manner.

78 Industrial robot safety has been addressed by the International Organization for Standardization
79 (ISO) through ISO 10218, entitled “Robots and robotic devices – Safety requirements for industrial
80 robots,” which was most recently updated in 2011 (ISO, 2011). A technical specification (ISO TS
81 15066), entitled “Robots and robotic devices – Safety requirements for industrial robots –
82 Collaborative operation” addresses industrial robot operation in the proximity of humans and is still
83 under development (ISO, 2014). This document provides information and guidance on how to
84 achieve the safety standards described in ISO 10218. A key element in these standards is the ability to

85 track people within a workspace and adjust robot motion according to the distance of separation
86 between the human and robot. Although industrial and agricultural applications are not directly
87 comparable, the ability to detect and localise nearby workers is a necessary condition for safe,
88 “human-aware” autonomous navigation in all application areas.

89 Significant research has been performed in the related area of pedestrian detection and tracking
90 in urban environments. Various active sensors such as ultrasound, radar or Lidar have been used for
91 pedestrian detection (Gandhi and Trivedi, 2007). Extensive research on passive imaging sensors and
92 computer vision has also been done (Dollar et al., 2012). Bellotto and Hu (2009) used both laser
93 scanner and vision to detect the upper and lower parts of humans. The potential utilisation of
94 pedestrian detection techniques for improving workforce safety in agricultural environments has been
95 discussed by Kohanbash et al., (2012). Freitas et al. (2012) use a 3D laser scanner to detect obstacles
96 and people moving at walking speed in front of an autonomous orchard vehicle. However, the ability
97 of cameras and laser scanners to detect humans can be affected by environmental conditions such as
98 low illumination, haze, fog, and rain. Also, such sensors require clear line of sight (LOS), and using
99 them to detect a worker who is located close to trees, or who is about to enter the robot’s current
100 orchard row from a neighbouring row can be very difficult due to severe LOS occlusion from tree
101 foliage.

102 The goals of this paper are to present the implementation of an ultra-wideband (UWB) radio-
103 based system for worker localisation in orchards, and to evaluate experimentally the accuracy and
104 availability of the system at locations within the driving reach of a moving vehicle in open space and
105 orchard environments, with and without interference from the human’s body. It is envisioned that
106 each worker will carry a mobile radio (and its small antenna), possibly attached to a belt on his/her
107 waist. Orchard vehicles will also carry ranging radios and the worker’s position will be estimated
108 using trilateration of the antenna-to-antenna distances between the worker and the vehicle antennas.
109 UWB transmission is a promising radio-based technology due to its power efficiency, fine spatial

resolution, and robust operation in harsh environments. The Federal Communications Commission (FCC) has recently allocated a spectral mask between 3.1–10.6 GHz for UWB. Our work is motivated by similar efforts that aimed at increased reliability in harsh work environments using radio beacons carried by workers. UWB ranging can provide a complementary human detection and localisation technology whose performance is less degraded in the poor visibility condition or real complex environment that plague other sensing technologies (Chang et al., 2009). UWB radios have been proposed for human detection and localisation in harsh environments associated with construction (Khoury and Kamat, 2009; Cheng, 2011; Niemeier et al., 2014) and mining (Chehri et al., 2009; Sunderman and Waynert, 2012). Results on tracking cows in a semi-open free-stall barn using a commercial system have also been reported (Porto et al., 2014).

This work investigates UWB operation in agricultural environments, because it is well known that the water contained in vegetation attenuates radio signals, and that signal reflection on the ground and scattering at tree branches introduce multipath effects that reduce accuracy (Vougioukas et al., 2013). Also, the presence of human bodies in the radio wave transmission path has been shown to affect ranging accuracy or even block transmission in indoors applications (Welch et al., 2002) and other confined spaces like mining (Mabrouk et al., 2012). Since the mobile antenna is to be carried by workers, human body interference in free/open space and in an orchard is examined.

2. Materials and Methods

An experimental position estimation system was developed to localise mobile UWB beacons that are to be carried by orchard workers. The mobile beacon antenna position coordinates were computed (with respect to a vehicle) by trilateration, using the measured ranges between the mobile beacon antenna and four beacon antennas on an autonomous vehicle. It is well known (Manolakis 1996) that three ranges suffice for trilateration on the plane. However, the LOS between a vehicle beacon and worker antennas will often be blocked in an orchard by vegetation or people. Furthermore, it has been shown (Zhou, 2011) that the estimation error and the uncertainty with four reference points tends to

be lower than that with three reference points when the object is located farther away; hence, four beacons were used for increased accuracy and redundancy. The accuracy and availability of the positioning system were assessed around the vehicle under static and dynamic walking-speed conditions, in open space and in an orchard.

2.1 Experimental materials

As shown in Fig. 1, the experimental system consists of several components. A computer-controlled electric utility vehicle (Sensible Machines, Pittsburgh, PA, USA) was used as a mobile platform that carries radio beacons. Four ranging radio receiver-transmitter units (P400 RCM, Time Domain, Huntsville, AL, USA) mounted on wooden poles on the vehicle were used as vehicle beacons. One P400 RCM radio carried by a person was used as a mobile beacon. One RTK GPS (AgGPS 542, Trimble, Sunnyvale, CA, USA) on the vehicle (referred to as “GPSv”) and an identical mobile RTK GPS (referred to as “GPSm”) carried by a person were used to measure vehicle and antenna locations. A serial to Wi-Fi adaptor (WA-232B, U.S. Converters LLC, Sedona, AZ, USA) was used to transmit the mobile GPS data to the data-logging computer. A Total Station (CST-305R, CST/berger, Watseka, IL) was used to measure true mobile antenna positions; it will be referred to as “TS”. The TS has 5-second angle accuracy at a sighting distance of 100 m, which is equivalent to an accuracy of 2.5 mm in distance measurement. A portable aluminium frame was constructed to carry the mobile beacon and the GPSm at various locations. The mobile beacon’s antenna was placed above the GPSm at a height equal to 0.9 m (human’s waist level), in a vertical orientation aligned to the vertical axis of the GPSm reference frame.

Fig. 1 - The UWB localisation system consists of: 1) utility vehicle, 2) four vehicle radio beacons, 3) mobile radio beacon, 4) mobile RTK GPS, 5) vehicle RTK GPS, and 6) Total Station.

The P400 RCM is an UWB radio transceiver that measures the distance between two P400 RCM antennas (Fig. 2). The units operate in the band of 3.1GHz to 5.3 GHz with a centre frequency at 4.3 GHz. In a static scenario (antennas not moving) with a clear LOS, the specifications for the range measurement precision and accuracy are 2.3 cm and 2.1 cm respectively. Each radio unit on the vehicle (referred to as “beacon”) reports its distance from the mobile radio every 20 ms within a maximum range of 125 m.

Fig. 2 - Radio unit A measures and reports the distance (red dotted line) between the centre points of antennas A and B.

171 In our experiments each range measurement was calculated as the median value of five consecutive
172 range measurements, in order to reject outliers. Hence, a new filtered range update was available for
173 each beacon approximately every 100 ms. The response times of the beacons would vary slightly and
174 therefore the update rate for trilaterated position estimates based on the range data was approximately
175 400 ms, i.e., 2.5 Hz. The GPS units were polled every 500 ms, i.e., at 2 Hz. Each beacon returns a
176 value of zero as range measurement if it does not get a response from the mobile radio (e.g., due to
177 obstacles in the transmission path) within the specified time window of 20 ms.

178 In this study the position of the mobile radio antenna was estimated via trilateration using the radio
179 beacons, and was measured directly using the GPSm or the TS. Positions measured by the TS were
180 considered to be the most accurate ones. However, the TS requires a stationary target and
181 unobstructed LOS from the target. Therefore, it could only be used for static tests in open space and in
182 the orchard when LOS was available. For dynamic tests and static tests without LOS the GPSm was
183 used as ground truth.

184 A multi-threaded data acquisition program was developed in Visual C++ to poll data from different
185 sources without response delays. One thread would poll sequentially the four vehicle beacons to
186 collect range data; a second thread would retrieve and parse the strings provided by the GPS receivers
187 and a third thread would log the data.

188

189 **2.2 System Coordinate frames**

190 The data collected from different devices had their own coordinate systems. To process the data, each
191 individual coordinate system was transformed into a single common primary coordinate system. The
192 GPS and the TS coordinate systems were transformed into the vehicle coordinate system. The
193 coordinate systems of the vehicle, $O_v(x_v, y_v, z_v)$, the TS, $O_{ts}(x_{ts}, y_{ts}, z_{ts})$, and the GPSv $O_g(x_g, y_g, z_g)$ are
194 shown in Fig. 3. The origin of vehicle coordinate system was placed at the same point as the origin of

the GPSv coordinate system. The geometric centreline (viewed from above the vehicle) is an imaginary line drawn from the centre of the rear axle to the centre of the front axle. The vehicle centreline was used to define the x-axis of the vehicle coordinate system. The angle θ between the y-axes of the GPSv and the vehicle coordinate systems was measured using the two RTK GPS units. The y-axis of the GPS coordinate system was set to the North direction, and the x-axis to the East direction. The orientations of the x- and y-axis were the same for the vehicle and the TS coordinate systems, albeit with different origins. The z-axes of the three coordinate systems were vertical upwards from the ground plane.

Fig. 3 - Coordinate frames of the vehicle, radio beacons, GPSv, GPSm, and TS.

The data measured in the GPSv coordinate frame were expressed in the vehicle frame as follows:

$${}^vP_G = {}^vR \cdot {}^GP = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^GP \quad (1)$$

where, vP_G is the coordinates vector of the position calculated by the GPS expressed in the vehicle frame, vR is the rotation matrix between the GPS and the vehicle frames, GP is the coordinates vector of points in the GPS frame, and ${}^vP_{G0}$ is the translation vector between the GPSv and vehicle coordinate frames. Similarly, the positions measured from the TS can be expressed in the vehicle

212 frame as follows:

$$213 \quad {}^V P = {}^V_T R \cdot {}^T P + {}^V P_{T0} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^T P + \begin{bmatrix} d_x \\ d_y \\ 0 \end{bmatrix} \quad (2)$$

214 where, ${}^V P_T$ is the coordinates vector of the position calculated by the TS in the vehicle frame, ${}^V_T R$ is
 215 the rotation matrix between the TS and vehicle frames, ${}^T P$ is the coordinates vector of points in the
 216 TS frame, ${}^V P_{T0}$ is the translation matrix between the TS and vehicle frames. Variables d_x and d_y ,
 217 represent the distances of two origins with respect to x and y axes of the vehicle coordinate system,
 218 which were measured using the TS at the beginning of each experiment.

219 2.3 Trilateration method and performance metrics

220 The antenna coordinates for vehicle beacon B_i be (x_i, y_i, z_i) ($i=1, 2, 3, 4$), and the true antenna
 221 coordinates of the mobile beacon B_m be (x_m, y_m, z_m) , are all expressed in the vehicle reference frame
 222 (Fig. 4). The vehicle beacon coordinates were: $B_1 = (-0.625, 1.348, 1.648)$; $B_2 = (0.623, 1.326, 1.185)$;
 223 $B_3 = (-0.675, -1.252, 1.172)$; $B_4 = (0.691, -1.282, 1.577)$. The positions were selected to minimise the
 224 expected mean square error in the mobile beacon position around the vehicle (He et al., 2014). The
 225 corresponding measured ranges from the vehicle beacons to the mobile beacon are r_1, r_2, r_3 , and r_4
 226 respectively.

228 **Fig. 4** - The illustration of four ranges from vehicle beacons to the mobile beacon.

229

230 The true distance d_i between the i th vehicle beacon and the mobile beacons is:

231
$$d_i = ((x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2)^{(1/2)} \quad (3)$$

232 The measured range r_i will contain some error ε_i , i.e.:

233
$$r_i = d_i + \varepsilon_i \quad (4)$$

234 Trilateration is used to estimate the coordinates of the mobile beacon based on the four measured
235 ranges. In the presence of range errors and absence of any prior information on the error statistics the
236 non-linear least-squares estimator is the optimal position estimator (Navidi et al., 1998). Hence the
237 trilateration equation is:

238
$$(x_r, y_r, z_r) = \arg \min_{x, y, z} \sum_{i=1}^4 (r_i - d_i)^2 \quad (5)$$

239 One important observation is that the range measurements r_1, r_2, r_3, r_4 in Eq. (5) are available at
240 times t_1, t_2, t_3, t_4 that are spaced 100 ms apart. In dynamic situations where the worker (and antenna) is
241 moving, these ranges do not correspond to a unique worker position, but rather to four distinct
242 positions that at walking speeds are very close to each other. Therefore, Eq. (5) will result in an
243 estimate that contains additional error, which is independent of the range error ε_i .

244 To evaluate the accuracy of the developed UWB localisation system, the trilaterated positions
245 (x_r, y_r, z_r) were compared to the ground truth (x_m, y_m, z_m) that was measured using the TS or GPSm.
246 The horizontal error in the xy plane, e_{xy} is:

247
$$e_{xy} = \sqrt{(x_r - x_m)^2 + (y_r - y_m)^2} \quad (6)$$

248 The error parallel to the vehicle's centreline (y-axis), e_y , and the error perpendicular to the vehicle
249 centreline, e_x are:

$$e_x = x_r - x_m, e_y = y_r - y_m \quad (7)$$

Given a set of N measurements, the system's accuracy was characterised using a number of metrics.

The first accuracy metric is the horizontal distance root mean square error (DRMS):

$$DRMS = \sqrt{\frac{1}{N} \sum_{i=1}^N (e_{xi}^2 + e_{yi}^2)} \quad (8)$$

In GPS literature the 2DRMS (twice the DRMS) is used extensively. The advantage of this metric is that it is a radial error, i.e., it is invariant to the rotation of the axes used to describe the error. However, in an orchard setting where a vehicle moves along rows with a well-defined motion axis that cannot change instantly, it is important to distinguish between errors along the motion – and tree row – axis, and errors perpendicular to it. Therefore, two additional metrics were computed, i.e., the average absolute errors in the x and y directions:

$$ABSE_x = \frac{1}{N} \sum_{i=1}^N |e_{xi}|, ABSE_y = \frac{1}{N} \sum_{i=1}^N |e_{yi}| \quad (9)$$

Two disadvantages of the above metrics are that isolated large outlier errors have a large effect on them, and that the metrics are not tied to a specific probability level. Therefore, the 95th percentile or R95 error metric is also computed based on e_{xy} . This metric is equal to the radius of a circle centred at the true position, containing the position estimate with probability of 95%. Finally, the (vertical) errors along the z -axis were ignored in this work.

In addition to position accuracy metrics, position *availability* was used to quantify the performance of the proposed localization method. Each set of four successive range requests by the vehicle beacons result in a quadruple (r_1, r_2, r_3, r_4) . Although in theory a 2D position can be derived from three ranges, preliminary experiments showed that when one range measurement was equal to zero (no response) other ranges were often very noisy and unreliable, and the estimated position contained very large errors. Therefore, in our experiments a range quadruple was considered 'valid' only if it contained no zeros; then, its corresponding position estimate was considered 'available'. So,

273 the position availability in a set of measurements was calculated as the ratio of the ‘available’ over all
274 the requested position estimates.

275 All post-processing calculations were performed using Matlab R2013a (MathWorks, Natick,
276 MA, USA), and the trilateration equation was solved using the *fminsearch()* Matlab optimisation
277 function. Regarding the error calculations, it is important to notice that in dynamic situations where
278 the worker carrying the antenna is moving, successive beacon ranges are spaced apart in time and
279 cannot be synchronised with GPSm measurements. All errors were calculated under the simplifying
280 assumption that the estimated worker position (x_r, y_r) has the same timestamp t_4 as the last range
281 measurement $\hat{r}_4$, and by selecting as ground truth the GPSm position whose timestamp was closest
282 (within ± 50 ms) to t_4 . In a real-time scenario this would require instantaneous calculation of Eq. (5).

283

284 **2.4 Experimental Design**

285 Autonomous vehicles in orchards are expected to travel inside orchard rows, in headlands and in open
286 space areas, such as farm roads. The vehicles are typically non-holonomic, with non-zero turning
287 radius, and hence cannot move sideways or make very sharp turns. The accuracy and availability of
288 the developed UWB radio localisation system were evaluated inside suitable ‘work zones’ in open
289 space and in an orchard.

290

291 **2.4.1 Static tests in open space**

292 For the open space static tests without any human body interfering in the antennas’ LOS, the work
293 zone was defined as a $24 \text{ m} \times 8 \text{ m}$ area with the vehicle at its centre; a rectangular grid of cell size 2 m
294 $\times 1 \text{ m}$ was used to sample this area uniformly (Fig. 5). The dimensions of the measurement area were
295 selected taking into account the locations where orchard workers may be present within the driving
296 reach of a moving vehicle in typical orchard configurations (4 m wide inter-row spacing). The line

297 defined by the vehicle's geometric centreline is labelled "1". The lines labelled "2" and "3" are two
 298 and four metres away from the centreline of the vehicle at its left and right sides, and are parallel to it.

299
 300 **Fig. 5 - Static test design in open space;** black dots represent the locations of the static test points.

301
 302 The localisation accuracy of the system was evaluated by moving the portable frame with the mobile
 303 beacon and GPSm on the nodes of the grid (black dots in Fig. 5), and by measuring the antenna
 304 position with the radio system, the GPS and the TS. Two hundred sets of four range measurements
 305 were taken at each node.

306 307 **2.4.2 Static tests in an orchard**

308 Experiments were conducted in an orchard managed by the University of California - Davis. The
 309 orchard contained central-leader Bartlett pear trees that were approximately 4 m high. The average
 310 height of the trunk from the ground to the first scaffolds, or major limbs, was 0.6 m (Fig. 6). The row
 311 spacing in the orchard was 3.6 m.

314

315 **Fig. 6** - Image from the pear tree orchard used for localisation experiments.

316

335 According to the experimental design, the work zone was defined as a $24\text{ m} \times 3.6\text{ m}$ area with the
336 vehicle at its right side, and the vehicle was placed to the right of a row at the edge of the orchard and
337 parallel to it (Fig. 7). The edge row was selected in order to provide enough distance between the TS
338 and the measurement points, so that the incidence angle of the laser beam on the antenna surface is
339 large (close to 90°) at all points. A large incidence angle translates to small laser beam trace on the
340 antenna (better accuracy) and to higher intensity for the reflected beam, which is required for valid
341 measurements. Orchard tests took place in late May and early June 2015 and the trees had full foliage;
342 fruit size was very small. During ‘static’ experiments the mobile radio antenna was held stationary
343 during all range measurements. During ‘dynamic’ experiments the antenna was moving relative to the
344 vehicle at walking speed.

Fig. 7 - Static test design in orchard environment; black dots represent the locations of the static test points.

The position error was assessed at three sets of points located on - or close to - three lines parallel to the TS's y-axis (Fig. 7; tree sketches are not drawn in scale). All points were spaced at approximately 1.0 m along the TS y-axis. Line No. 1 was defined by the geometric centreline of the vehicle. Line No. 2 was defined by the tree trunks; however, the actual measurement positions were on points along the peripheries of the canopies where GPS signal was available. Line No. 3 was the middle-row line between two consecutive tree rows to the left of the vehicle. Points on this line correspond to possible locations of orchard workers working and walking in proximity to the vehicle without clear LOS from the vehicle. Detecting and localising workers on points on line No. 3 would be challenging for any detection system relying on optics (camera, laser) because worker visibility is severely restricted by tree trunks and foliage. The true positions for the points on line No. 3 were to be measured using the GPSm only, because tree foliage blocked their line of sight from the TS. Two hundred sets of four range measurements were taken at each point on each line.

2.4.3 Dynamic tests in open space and orchard

In order to evaluate the accuracy of the developed radio localisation system when the mobile and beacon antennas move with respect to each other, dynamic tests were designed in open space and in an orchard; no human bodies interfered in the antennas' LOS during these tests. During these tests the antenna was moved relative to the vehicle at slow walking speed, close to 1 km h^{-1} . A slow speed was selected because this paper focuses on autonomous labour-aid vehicles, where the relative speeds between workers and vehicles are small (workers may pick fruits, prune, perform flower-thinning, etc.).

The dynamic tests in open space were designed to take place on the paths defined by the lines labelled "1", "2" and "3", as shown in Fig. 8a; these were defined in the same manner as the lines in the static tests (Fig. 5). Similarly, the orchard dynamic tests were designed for the paths defined in the static orchard tests. As shown in Fig. 8b, one path was along the centreline of the vehicle (line 1), another path was along the peripheries of the tree canopies (path 2) and a third path was at the middle of the neighbouring row (line 3). Each path was traversed ten times.

Fig. 8 - Dynamic test paths in: (a) open space, and (b) in an orchard.

2.4.4 Human body interference

360 As explained in the introduction, it is envisaged that each worker would carry a mobile UWB
361 radio and an antenna that is attached to a belt on his/her waist. It has been shown experimentally
362 (Welch et al., 2002) that the human body causes severe signal attenuation when it stands in the LOS
363 between an antenna attached to the body and an antenna far from it. Therefore, in a light multipath
364 environment where the signals exchanged between the wearable antenna and the receiving beacons
365 travel directly and not via reflections, the power received from the wearable antenna depends strongly
366 on the person's orientation with respect to the receiving beacon (degree of LOS blocking). This
367 dependence is greatly reduced in dense multipath environments where signals make it to the receiving
368 beacon via reflections (Welch et al., 2002). Localisation accuracy of a wearable antenna in an indoor
369 light multipath environment has been recently explored experimentally at close range (inside a 1.5 mx
370 1.5 m area) and shown to depend on body angle (Bharadwaj, 2015). UWB-based localisation
371 availability and accuracy at large distances and in the presence of foliage has not been reported in the
372 literature.

373 In order to evaluate human body interference in our proposed localization scenario where the
374 beacons are on a vehicle, the antenna was placed on a belt attached to the waist of a walking person,
375 and two sets of experiments were performed: one in open space and one in the orchard.

376 In the open-space set of experiments, the vehicle was positioned at a location where there were
377 no nearby objects or trees that could reflect the signals between the wearable antenna and the vehicle
378 beacons. The person carrying the UWB radio and antenna walked on lines 1, 2 and 3 as shown in Fig.
379 8a. Since we know that body orientation is important for LOS communication between antennas, and
380 given that in real situations a worker's orientation with respect to the vehicle antennas will be random,
381 two experiments were performed in open space. In the 'best case' experiment the person walked
382 making sure that the wearable antenna always faced the vehicle beacons and had unobstructed LOS
383 with all of them. In the 'worst case' experiment the walking person's body always blocked completely
384 the LOS between the wearable antenna and each of the vehicle beacons. From now on, these

385 experiments will be referred to as ‘full-LOS’ and ‘no-LOS’ experiments respectively. The accuracies
386 and availabilities calculated from these experiments offer bounds of performance for real-life orchard
387 activities. Each experiment was replicated ten times.

388 In the orchard set of experiments the person walked along the lines 1, 2 and 3 shown in Fig. 8b.
389 The first orchard experiment was a full-LOS one, and the second experiment was a no-LOS one, as
390 these were described in the previous paragraph; each experiment was replicated ten times.

391 **3. Results and discussion**

392 **3.1 Open-space results**

393 **3.1.1 Static tests in open space**

394 The antenna positions at the grid points were measured using the TS and GPSm, and were estimated
395 using UWB ranging and trilateration; these positions are shown in Fig. 9 for a specific test. The TS
396 measurements are not visible at many locations because they lie below the dots representing the
397 GPSm measurements. The DRMS and R95 metrics for the distance between the TS and GPSm
398 measurements were 1.8 cm and 3.2 cm respectively, whereas the maximum distance was 4.0 cm.
399 Furthermore, a two-sample Kolmogorov-Smirnov test verified that the error data with TS and GPSm
400 as ground truth have the same distribution at the 5% significance level. Hence, for the purposes of this
401 work the TS and GPSm provide adequate accuracy and can be used interchangeably as ground truth in
402 open-space tests.

Fig. 9 - Open-space static test: positions measured with TS and GPSm and estimated via trilateration in a specific test. Diamonds represent TS measurements; dots represent GPSm measurements; squares represent the average trilateration estimate for each position.

The position errors are illustrated in Table 1 and Table 2, using TS and GPSm as ground truth respectively.

Table 1 - Open-space static accuracy metrics using TS as ground truth (units in cm).

	DRMS	ABSE _x ± std	ABSE _y ± std	R95
Line 1	17.7	13.6 ± 8.8	5.5 ± 4.8	33.9
Line 2	14.5	10.9 ± 7.8	4.7 ± 3.5	26.7
Line 3	13.3	8.1 ± 6.8	6.5 ± 4.7	24.3
Front-all	12.4	9.2 ± 6.5	3.8 ± 3.7	24.1
Rear-all	17.0	11.6 ± 9.0	7.7 ± 4.2	33.6
All points	14.8	10.3 ± 7.8	5.6 ± 4.4	27.2

Table 2 - Open-space static accuracy metrics using GPSm as ground truth (units in cm).

DRMS	ABSE _x ± std	ABSE _y ± std	R95
------	-------------------------	-------------------------	-----

Line 1	17.1	13.3 ± 8.1	2.3 ± 4.9	30.7
Line 2	13.8	10.5 ± 7.1	3.5 ± 3.4	24.8
Line 3	13.4	8.0 ± 7.1	5.0 ± 4.7	25.6
Front-all	13.0	9.7 ± 6.9	3.9 ± 3.7	25.5
Rear-all	15.9	10.4 ± 8.2	7.9 ± 4.1	30.6
All points	14.4	10.0 ± 7.5	5.8 ± 4.4	25.7

416

417 Both tables show that the ABSE_x errors are significantly larger than the ABSE_y errors along each
 418 line. A two-sample Kolmogorov-Smirnov test was applied on the ABSE_x and ABSE_y errors and the
 419 hypothesis that these errors come from identical distributions was rejected (5% significance).

420 As will be explained next, the explanation for this lies in two factors: a) the geometrical configuration
 421 of the vehicle beacons and its effect on precision along the orthogonal axes; and b) the geometry of
 422 the work zone. It is known (Navidi et al., 1998) that for orthogonally placed beacons (like the B_is) the
 423 asymptotic variances of the non-linear least-squares estimator (x_r, y_r) for the trilaterated coordinates in
 424 the x and y -axes are:

425

$$\text{var}(x_r) = \frac{\sigma^2}{\sum_{i=1}^4 \frac{(x_m - x_i)^2}{d_i^2}}, \text{var}(y_r) = \frac{\sigma^2}{\sum_{i=1}^4 \frac{(y_m - y_i)^2}{d_i^2}} \quad (10)$$

426 where σ^2 is the variance of the range error. The mean absolute errors ABSE_x and ABSE_y are
 427 proportional to $\text{var}(x_r)$ and $\text{var}(y_r)$ respectively. The reason is that the errors e_x and e_y follow normal
 428 distributions (verified via a one-sample Kolmogorov-Smirnov test). The absolute values $|e_x|$ and $|e_y|$
 429 follow *folded normal distributions*, and the mean of the folded normal distribution is proportional to
 430 the variance of the original normal distribution (Leone, Nottingham & Nelson, 1961). Theoretical
 431 evaluation of Eq. (10) was performed on a 24 × 24 m region centred at the vehicle. The value of each
 432 pixel in Fig. 10 shows whether the ratio ABSE_x/ABSE_y is greater, less or equal to one. The figure
 433 reveals that accuracy along the y -axis is expected to be better (ABSE_y < ABSE_x) at all locations
 434 inside the vertical cone-shaped regions. This fact, combined with the fact that the experimentally

435 measured locations lie predominantly inside the vertical conical region explain why ABSE_x errors are
 436 significantly larger than ABSE_y errors in Tables 1 and 2. One could argue that the accuracy results
 437 are ‘biased’. However, it should be kept in mind that the goal of this work is to evaluate the
 438 localisation performance inside the work zone, i.e., at locations within the driving reach of a moving
 439 vehicle where a collision is possible. The geometry of the work zone serves this goal, and
 440 consequently affects the statistics of all reported results.

441
 442 **Fig. 10** - Theoretical ratio ABSE_x/ABSE_y (Eq. 10) calculated over a 24×24 m region centred at the
 443 vehicle. Dots represent actual locations of measurements. Each pixel value encodes whether the ratio
 444 ABSE_x/ABSE_y is greater, less or equal to one. Diagonals and circle around vehicle are loci of points
 445 where the ratio is equal to one. ABSE_y < ABSE_x inside the cone-shaped regions aligned with the y-
 446 axis; ABSE_x < ABSE_y inside the cone-shaped regions aligned with x-axis.

447
 448 In terms of range, a worker’s position estimate is expected to get worse as distances d_i increase.
 449 Figure 11 shows the DRMS and R95 metrics of all points at increasing distances of the mobile
 450 antenna position from the vehicle’s frame origin; ground truth is measured with GPSm. As distance
 451 grows, more position measurements lie within this distance and more coordinates are included in the

452 calculations of the metrics.

Fig. 11 - DRMS and R95 metrics as functions of distance in open-space static tests.

453

454 The DRMS metric at 12.2 m increased by 26.2% compared to its value at 3m. The corresponding R95
455 value grew by 50.6%, i.e. twice as much. This means that there is more variance as the antenna moves
456 farther away from the vehicle. To verify this, Fig. 12a and Fig. 12b show the ABSE_x and ABSE_y
457 metrics respectively (and their standard deviations) of all points, at increasing distances of the
458 measured position from the vehicle's frame origin. From the figures it can be seen that standard
459 deviation of the absolute error along the *x*-axis at 12.2m grew by 42.8% compared to its value at 3m.
460 The corresponding number along the *y*-axis was 30%.

Fig. 12 - (a) ABSE_x and (b) ABSE_y metrics plotted as a function of distance in open-space static tests.

The above results can be interpreted by looking at the spatial distributions of the theoretically predicted error variances $\text{var}(x_r)/\sigma^2$ (Fig. 13a) and $\text{var}(y_r)/\sigma^2$ (Fig. 13b), as these can be computed using Eq. (10). Figure 13a shows that ABSE_x increases at greater distances along Lines 1 and 2. In our work zone, the greater the distance from the vehicle, the larger the number of points with large y values that are included in the metric calculation. Hence, ABSE_x increases (as shown in Fig. 12a) and results in higher DRMS (and R95) error (as shown in Fig. 11). On the other hand, Fig. 13b shows that ABSE_y does not increase significantly within the $|x| \leq 4$ m zone; this is reflected in the ABSE_y metric in Fig. 12b.

Finally, the availability computed over all static test points was 100%.

Fig. 13 - Spatial distributions of theoretical error variances in open-space static tests: (a) $\text{var}(x_r)/\sigma^2$ and (b) $\text{var}(y_r)/\sigma^2$. ABSE_x and ABSE_y are proportional to the respective variances.

3.1.2 Dynamic tests in open space

488 For the dynamic tests the GPSm measurements were used as ground truth, since TS cannot track a
 489 moving target. Care was taken to avoid blocking the LOS between the mobile and vehicle beacons. In
 490 all data processing for dynamic tests, range data sets (r_1, r_2, r_3, r_4) that contained one or more zeros
 491 were not used. Figure 14 shows one repetition (out of ten) of the measured and estimated points on
 492 the traversed paths; gaps in the paths indicate missing GPS data or the existence of zero range
 493 measurements.

484
 487 **Fig. 14** - Example path during open-space dynamic tests. Dots and squares represent GPSm
 488 measurements and trilateration estimates respectively.

487
 488
 493 Table 3 shows the position accuracy metrics calculated from points on the different paths. The
 494 number of valid position measurements varies because of not exactly equal path lengths, and sporadic
 495 zero readings.

492

Table 3 - Open-space dynamic accuracy metrics using GPSm as ground truth (units in cm).

	DRMS	ABSE _x ± std	ABSE _y ± std	R95
Line 1 (1154 points)	22.7	14.6 ± 7.3	7.7 ± 2.4	43.8
Line 2 (1756 points)	31.8	19.3 ± 6.1	11.7 ± 3.4	59.5
Line 3 (1604 points)	36.5	21.3 ± 6.3	15.2 ± 3.4	67.2
Front-overall (2297 points)	32.0	17.1 ± 6.1	15.7 ± 6.5	51.1
Rear-overall (2217 points)	31.1	20.6 ± 8.4	8.0 ± 2.7	65.9
All points (4514 points)	31.6	18.8 ± 7.2	11.9 ± 4.6	58.1

The mean absolute errors along the x -axis (ABSE_x) were larger than the corresponding y -axis errors (ABSE_y), just like in the static open-space tests. The ABSE_x of all the data points was 1.6 times larger than the corresponding ABSE_y. The same was true for their variances. A two-sample Kolmogorov-Smirnov test verified that ABSE_x and ABSE_y do not come from the same distribution (5% significance).

To illustrate the effect of outlier range measurements, the error frequency histogram and the fitted error cumulative density function for the horizontal distance error e_{xy} of all measured points is shown in Fig. 15. To calculate the cumulative density function (cdf) a nonparametric representation of the error probability density function (pdf) was fitted to the data using MATLAB's *fitdist()* function and the Epanechnikov kernel and the cdf was obtained from this pdf.

Fig. 15 - Open-space dynamic tests: Horizontal distance error histogram and its fitted cumulative probability density function for all points (units in cm).

Figure 16 shows the DRMS and R95 metrics as functions of distance of the mobile antenna position from the vehicle frame's origin.

Fig. 16 - DRMS and R95 metrics as functions of distance in open-space dynamic tests.

The DRMS metric at 12.2 m increased by 58.2% compared to its value at 3m. The R95 value between these two distances grew by 114.3%. Clearly, as worker-vehicle distance increases, accuracy suffers and precision worsens because of increased variance and outliers.

523 The open-space static and dynamic error results can be compared by considering Fig. 11 and Fig. 16.
524 At 3m, the static DRMS and R95 were 11.4 cm and 17.1 cm and the respective dynamic metrics were
525 20.0 cm and 27.1 cm; these values translate into respective error differences of 75.4% and 50.6%. At
526 12.2 m, the static DRMS and R95 were 14.4 cm and 25.7 cm and the respective dynamic metrics were
527 31.6 cm and 58.1 cm; these values translate into error differences of 119.4% and 114.3% respectively.
528 The above numbers indicate that in dynamic trilateration the position error was 1.6 to 2.2 times as
529 large as the static error at the same distance. This is explained primarily by the *non-collocation of*
530 *measurements*, i.e., the fact that the range measurements r_1, r_2, r_3, r_4 in Eq. (5) are available at times
531 t_1, t_2, t_3, t_4 that are spaced 100 ms apart; hence they do not correspond to a unique antenna/worker
532 position, but rather to four distinct positions. Therefore, Eq. (5) will result in an estimate that contains
533 two independent sources of error: the dynamic non-collocation error, and the range error ε_i that enters
534 Eq. (5) in both static and dynamic conditions.

535 Finally, the availability computed over all dynamic open-space test points was 99.5%.

536

537 **3.1.3 Human body interference in open space**

538 The no-LOS and full-LOS experiments were conducted as described in the experimental design
539 section 2.4.4. The position availability for the no-LOS experiments was only 11.1% and when
540 positions were available the errors were very large. The DRMS over all available position
541 measurements (296 samples) was 819.7 cm and the R95 was equal to 2495 cm. Clearly, ranging in
542 open space when the human body blocked the LOS completely was unreliable both in terms of
543 accuracy and availability. This is in agreement with results reported by Welch et al. (2002).

544 The position availability of the full-LOS experiments was 99.7%. The accuracy metrics are
545 given in Table 4.

546

547 **Table 4** - Open-space dynamic accuracy metrics with full-LOS body interference using GPSm as

548 ground truth (units in cm).

549

	DRMS	R95
Line 1 (999 points)	49.2	73.1
Line 2 (2047 points)	69.7	65.9
Line 3 (1764 points)	43.7	62.8
Front-overall (2634 points)	45.9	68.8
Rear-overall (2176 points)	69.7	68.9
All points (4810 points)	57.90	68.9

550

551 The fact that DRMS was higher than R95 on Line 2 behind the vehicle led to further analysis of the
552 data. It was found that 0.6% of the errors were above 200 cm and that two (out of 4514) consecutive
553 position estimates had errors equal to 1745 and 1684 cm respectively. These two position estimates
554 increased significantly the DRMS without affecting the R95. Removing these two outlier data points
555 reduced the overall DRMS to 46.9 cm; R95 remained essentially the same at 68.5 cm. Compared to
556 the open-space results without body interference in Table 3, the overall DRMS increased significantly
557 (83.2% including the outliers; 48.7% without them), whereas the R95 error increased slightly (18.6%).
558 The presence of the human body in close proximity to the antenna affected negatively the localisation
559 accuracy – but not the availability – in open space when LOS was available.

560 **3.2 Orchard test results**

561 **3.2.1 Static tests in the orchard**

562 The points on lines No. 1 (vehicle centreline) and No. 2 under (edges of tree canopies) were measured
563 using TS and GPSm, while the points on line No. 3 (neighbouring row centre-line) were measured

570 using only GPSm due to lack of unobstructed LOS from the TS. The measurement locations are
 571 shown in Fig. 17 for a specific test. The TS measurements are not visible at many locations because
 572 they lie below the dots representing the GPSm measurements.

569
 574 **Fig. 17** - Measured and trilaterated positions in the orchard static test during a specific test. Diamonds
 575 represent TS measurements; dots represent GPSm measurements; squares represent the average
 576 trilateration estimate for each position.

573
 586 Table 5 contains the accuracy metrics for line 1 and line 2 using TS as ground truth. Overall, when the
 587 mobile antenna was under - or partially under - trees (line 2) the trilaterated error was higher than
 588 when the antenna was 1 m away to the right of the tree row (line 1). This was supported by two-
 589 sample Kolmogorov-Smirnov tests that were applied on the e_x , e_y , $|e_x|$, $|e_y|$, and e_{xy} error pairs on the
 590 two lines; the hypotheses that these errors come from the same distribution were rejected (5%
 591 significance). The ABSE_x errors were significantly larger than the ABSE_y errors, as was observed in
 592 the open-space experiments.

Table 5 - Orchard static accuracy metrics using TS as ground truth (units in cm).

	DRMS	ABSE _x ± std	ABSE _y ± std	R95
Line 1	20.9	15.9 ± 13.1	3.0 ± 2.9	41.9
Line 2	27.2	24.4 ± 14.9	3.6 ± 4.1	52.2
All points	24.4	19.3 ± 14.2	3.3 ± 3.5	45.8

Figure 18 shows the DRMS and R95 metrics for all points on Lines 1 and 2 combined, as functions of distance of the mobile antenna position from the vehicle's frame origin; ground truth was measured with TS.

Fig. 18 - DRMS and R95 metrics as functions of distance in orchard static tests.

The DRMS error at 12.2 m was 24.3 cm and increased by 235% compared to its value at 3m; the corresponding R95 value was 45.8 cm and increased by 349%. A comparison between Fig. 11 and Fig. 18 for the static tests reveals that the orchard static DRMS is comparable to the open-space DRMS when the antenna is close to the vehicle, and that it increases faster as distance increases, becoming almost twice as large as the open-space DRMS at 12.2 m. A similar trend is present for the R95 accuracy metric.

The results shown in Table 4 and Fig. 18 suggest that the presence of trees – especially in LOS -

594 affects negatively the positioning accuracy of the trilateration system. An explanation is that as
595 distance increases, more foliage enters in the propagation paths of the radio signals of the four vehicle
596 beacons, and the resulting increased scattering and multipath introduce larger errors ε_i , which can be
597 significantly different for each beacon (Al-Nuaimi & Hammoudeh, 1994). These errors enter into Eq.
598 (5) and degrade the trilateration position estimate.

599 In order to assess the trilateration accuracy between tree rows and to compare static and dynamic
600 accuracies, RTK GPS data must be used as “ground truth”, since the TS laser beam can neither “see”
601 the mobile antenna on line 3 or track the moving antenna on any path. However, it is known that RTK
602 GPS accuracy and precision degrade when the antenna is under - or close to - tree canopies because of
603 reduced signal strength and multipath/scattering effects while the electromagnetic wave is penetrating
604 the branches and canopies of trees. Various researchers (e.g., Lee an Ge, 2006; Brach & Zasada,
605 2014) have reported RTK GPS DRMS static errors in the order of 10 - 40 cm or more, when the GPS
606 antenna is near or under trees, using TS as ground truth. In order to compare TS and GPSm
607 measurements in our orchard, the DRMS and R95 metrics were computed independently for Line 1
608 and Line 2. TS measurements were treated as “absolute ground truth”, since they are not affected by
609 foliage. On Line 1, DRMS and R95 were 11.8 cm and 20.9 cm respectively. The corresponding
610 values were 1.8 cm and 3.2 cm in the open-space tests. Clearly, the presence of the trees affected RTK
611 GPS accuracy of positions on line 1, although the measurement points were not under the tree
612 canopies. Points on line 2, which were partially under the tree canopies, had higher DRMS and R95
613 values than line 1, equal to 14.1 cm and 24.1 respectively.

614 Obviously, the GPSm cannot be used to provide accurate measurements of the true antenna positions,
615 like in the open-space experiments, because it adds a significant - independent - error to the measured
616 position. Keeping in mind that DRMS and R95 correspond to radii of circles around the true position,
617 GPSm measurements can be used to provide *upper bounds* of the trilaterated errors. These bounds are
618 simply the sums of two radii around the true position, i.e., the trilaterated-versus-GPSm error metrics

619 and the GPSm-versus-TS position error metrics (11.8 cm and 20.9 cm respectively).

620 Table 6 presents the trilaterated-versus-GPSm accuracy bounds for line 1 and line 3. The calculated
621 error bounds are conservative and sometimes can be much larger than the actual errors. For example,
622 a comparison between the error metrics along Line 1 from Table 4 (ground truth TS; first row) and
623 Table 5 (ground truth GPSm; first row) reveals that in these tests the upper bounds were
624 approximately twice as large as the measured values (e.g., DRMS bound is 42.1 cm, whereas DRMS
625 is 20.9 cm).

626

627 **Table 6** - Static position error bounds in an orchard using GPSm as ground truth (units in cm). Each
628 bound value is the sum of two errors: trilaterated-versus-GPSm error (left term in parenthesis) and
629 GPSm-versus-TS position error (right term in parenthesis).

630

	DRMS upper bound	R95 upper bound
Line 1	42.1 (30.3 + 11.8)	78.0 (57.1 + 20.9)
Line 3	36.5 (24.7 + 11.8)	71.9 (51.0 + 20.9)
All points	39.3 (27.5 + 11.8)	78.1 (57.2 + 20.9)

631

632 In the orchard, static testing availability was 100% and the tree trunks and low-height foliage in this
633 orchard did not block radio communication among the beacons within the tested range.

634

635 3.2.2 Dynamic tests in the orchard

636 During dynamic testing, a human carried the mobile radio and GPSm while walking on the paths
637 specified by the experimental design and staying away from the antennas' LOS and from the mobile
638 antenna itself. The GPSm was used as ground truth. Fig. 19 shows a sample path. The corresponding
639 errors for line 1 and line 3 are given in Table 7. Error data for points on line 2 are not available due to
640 foliage blocking the GPSm signal. As with the open-space dynamic tests, statistics were calculated
641 based on varying sample size because of different path lengths and sporadic zero readings.

Fig. 19 - Points on a sample path during dynamic testing in the orchard without body interference. Dots and squares represent GPSm measurements and trilateration estimates respectively.

Table 7. Dynamic position error bounds in an orchard using GPSm as ground truth (units in cm). Each bound value is the sum of two errors: trilaterated-versus-GPSm error (left term in parenthesis) and GPSm-versus-TS position error (right term in parenthesis).

	DRMS upper bound	R95 upper bound
Line 1 (1164 points)	44.8 (33.0 + 11.8)	83.1 (62.2 + 20.9)
Line 3 (947 points)	76.6 (64.8 + 11.8)	147.0 (126.1 + 20.9)
All points (2111 points)	61.6 (49.8 + 11.8)	116.7 (95.8 + 20.9)

A direct comparison of Tables 6 and 7 reveals a small increase in the upper bounds of the DRMS and R95 positioning errors on line 1, and a dramatic increase (doubling) of these error bounds along Line 3, which lies in the middle between two tree rows on the left side of the vehicle. A statistical two-sample Kolmogorov-Smirnov test verified that the errors did not follow the same distribution. This can be attributed to the combined effects of the dynamic non-collocation error in the range measurements (moving antenna) and the multipath error due to signal scattering and reflection in the

657 presence of tree foliage. Finally, position availability during dynamic testing was 97.5%.

658

659 3.2.3 Human body interference in the orchard

660 The experiments for human body interference in the orchard were conducted as described in the

661 experimental design section 2.4.4. Improved GPS conditions enabled measurements at the periphery

662 of the tree canopies (line 2 of Fig. 8b). Figure 20 shows the paths traversed during one repetition (out

663 of ten) of the full-LOS experiments.

664

665 **Fig. 20** - Points on a sample path during dynamic testing in the orchard with full-LOS and body
666 interference. Dots and squares represent GPSm measurements and trilateration estimates respectively.

667

668 The position availability of the full-LOS experiment was 99.3%. The availability of the no-LOS

669 experiment was 60.2%; much lower than the full-LOS availability, but significantly higher than the

670 measured open-space availability (11.1%). This increase can be attributed to the presence of trunks

671 and branches, which seem to have allowed for multi-path propagation. This finding is in agreement

672 with published results (Welch et al., 2002).

673 The upper bounds of the DRMS and R95 error metrics (GPSm uncertainty is added) for the full-LOS
674 and no-LOS experiments are shown in Tables 8 and 9 respectively. The calculation of the errors for
675 all points did not include line 2 in order to enable comparison between Table 7 and Table 8.

676

677 **Table 8** - Upper bounds of position errors in full-LOS body interference experiments in the orchard
678 (units in cm). Each bound value is the sum of two errors: trilaterated-versus-GPSm error (left term in
679 parenthesis) and GPSm-versus-TS position error (right term in parenthesis).

680

	DRMS upper bound	R95 upper bound
Line 1 (1709 points)	59.2 (47.4 + 11.8)	82.5 (61.6 + 20.9)
Line 2 (1903 points)	56.1 (44.3 + 11.8)	86.0 (65.1 + 20.9)
Line 3 (1754 points)	67.1 (55.3 + 11.8)	135.2 (114.3 + 20.9)
All points (Lines 1+3) (5366 points)	63.4 (51.6 + 11.8)	108.0 (87.1 + 20.9)

681

682

683 **Table 9** - Upper bounds of position errors in no-LOS body interference experiments in the orchard
684 (units in cm). Each bound value is the sum of two errors: trilaterated-versus-GPSm error (left term in
685 parenthesis) and GPSm-versus-TS position error (right term in parenthesis).

686

	DRMS upper bound	R95 upper bound
Line 1 (645 points)	138.7 (126.9 + 11.8)	278.9 (258.0 + 20.9)
Line 2 (738 points)	105.2 (93.4 + 11.8)	150.7 (129.8 + 20.9)
Line 3 (487 points)	127.6 (115.8 + 11.8)	181.5 (160.6 + 20.9)
All points (Lines 1+3) (1870 points)	123.6 (111.8 + 11.8)	217.8 (196.9 + 20.9)

687

688

689 A statistical two-sample Kolmogorov-Smirnov test between the error data from the dynamic orchard

690 experiments without antenna-body proximity (Table 7) and the full-LOS experiments with the body in
691 close proximity to the antenna (Table 8) showed that the errors do not follow the same distribution.
692 The upper bound of the localisation error along line 1 increased from 44.8 cm to 59.2 cm. Given that
693 tree interference is minimal along this line, this increase can be attributed to the proximity of the
694 body. On line 3 where the trees and body form a dense multi-path environment, the proximity of the
695 body seems to slightly reduce the error. Overall, the errors were comparable and body proximity did
696 not seem to increase errors significantly. The no-LOS experiment resulted in errors that were typically
697 twice as large as the full-LOS errors. This can be explained by the fact that radio communication was
698 made possible mostly via multipath propagation, as attested by the increased availability in the
699 orchard compared to that of open space.

700

701 **4. Conclusions**

702 An ultra-wideband radio-ranging and trilateration system was developed to localise workers in
703 orchards. Trilateration was performed based on four range estimates between a vehicle's beacon
704 antennas and the antenna of a mobile radio unit, which was carried by a human. The system's
705 position-estimation accuracy and availability were assessed at locations close to the vehicle in a
706 variety of conditions. In the absence of a human close to the mobile antenna, localisation was tested
707 when the antenna was static and when it was moving, both in open space and in an orchard. When a
708 human carried the antenna on a belt (close proximity) and walked, localisation was tested in open
709 space and in an orchard, with full and zero LOS availability. The major conclusions of this study can
710 be summarised as follows.

711 **4.1 Effects of vehicle beacon configuration**

712 In the open-space static and dynamic tests, and in the orchard static tests, the mean absolute error
713 along the vehicle's heading (ABSEy) ranged from 3.3 cm to 11.9 cm, and was 1.6 to 5.8 times smaller

than the error along the axis perpendicular to the vehicle (ABSE_x). Also, although accuracy decreased with increasing distance (Fig. 11), the accuracy along the vehicle's axis (ABSE_y) did not change significantly within the $|x| \leq 4$ m work zone (Fig. 12b). This was due to the geometrical configuration of the vehicle beacons, and the geometry of the work zone (Figs. 10, 13a, 13b). The fact that ABSE_y was smaller than ABSE_x is favourable, because accurate worker localisation in the vehicle's direction of motion may enable more effective braking decisions.

4.2 Effects of moving (vs. static) antenna without antenna-body proximity.

When the antenna was moving, the accuracy of the trilateration system was worse than in static conditions. In open space and in the orchard, the DRMS and R95 position errors at walking speed were 1.6 to 2.2 times larger than the corresponding errors at the same distance under static conditions (Tables 2, 3, 6, 7). This is explained primarily by the *non-collocation of measurements*, i.e., the fact that the four ranges used for trilateration do not correspond to the same position. The non-collocation error could be lowered if range measurements were not filtered in real time, thus increasing the beacons' polling rate. Such an approach would increase the range error variance, so its benefits must be examined in real conditions. Given that vehicles and workers in orchards do not move at high speeds, this error is not expected to prohibit the use of active beacons for trilateration.

4.3 Effects of presence of trees without antenna-body proximity

The accuracy of the trilateration system in the orchard was worse than in open space. The position error in the orchard was higher under both static (Table 2, DRMS 14.4 cm vs. Table 6 DRMS 39.3 cm) and dynamic conditions (Table 3, DRMS 31.6 cm vs. Table 7, DRMS 61.6 cm). This can be attributed to *multipath error* due to signal scattering and reflection from tree trunks and foliage. Closer to the vehicle, the DRMS and R95 errors in the orchard were comparable to the open-space errors, but grew faster than open-space errors as distance increased; at a distance of approximately 12 m they were almost twice as large (Figs. 11, 18). Overall, the trees in the orchard did not seem to

739 block radio communication among the beacons at the tested distances (< 12.2 m). In open space the
740 availability over all test points was 100% and 99.5% for static and dynamic tests respectively. In the
741 orchard, static testing availability was 100% and during dynamic testing it dropped to 97.5%. It is
742 expected that some predictive filtering could compensate for short-time data outages.

743

744 **4.4 Combined effects of moving antenna and tree-presence without antenna-body proximity**

745 In the dynamic experiments in the orchard, when the antenna was carried between tree rows to the
746 side of the vehicle (line 3, Tables 6, 7) the bounds of the DRMS and R95 position errors were almost
747 twice as high as the corresponding errors on line 1. Given that a row of trees stood between the
748 vehicle and the moving antenna, this large increase in error could be attributed to the combined
749 effects of the dynamic non-collocation error and the foliage-induced multipath error. However,
750 positioning accuracy is not critical when a worker works in a different row than the vehicle because a
751 collision with the worker is not possible.

752

753 **4.5 Effects of antenna-body proximity with antenna moving at walking speed**

754 When the human body blocked completely the signal propagation among antennas (no-LOS),
755 trilateration in open space was completely unreliable, both in terms of accuracy and availability.
756 Under the same no-LOS conditions in the orchard, the availability increased more than five times, due
757 to multi-path propagation; however, the accuracy was still extremely poor (Table 9). This is a very
758 important shortcoming, because the proposed system relies on radio antennas carried/worn by
759 workers. A possible solution would be to use two antennas on opposite sides of the body (e.g., left-
760 and-right on a belt), so that full-LOS is available most of the time (P400 RCM supports two
761 antennas). Another – perhaps complementary – approach is to use a filter (e.g., Kalman) to calculate
762 worker positions during short-time data outages.

Under full-LOS conditions, the localisation accuracy over all points in open space decreased significantly compared to that without antenna-body proximity (Tables 3, DRMS 31.6 cm vs. Table 4, DRMS 57.9). However, under full-LOS in the orchard, the accuracy and availability were similar with and without antenna-body proximity (Table 7, DRMS 61.6 cm vs. Table 8, DRMS 63.4 cm). This finding is very promising for localisation in orchard settings and could be attributed to the multi-path environment created by the combination of trunks, branches, leaves and the human body, which allowed for multi-path signal propagation. Also, the position availability with full-LOS was very high 99.3% and indicated that the proximity of the worker's body was not significant.

771

In overall conclusion, active radio ranging and trilateration seems to offer a workable approach for human detection and localisation by vehicles moving slowly in orchards. Of course, each worker would need to carry an active beacon. However, the system would not rely on cameras, laser scanners and advanced perception algorithms, although it could be used in addition to them as a complementary sensing modality. Issues related to sporadic position unavailability and outlier errors (R95 much higher than DRMS) could be addressed by suitable filtering. As the need for autonomous vehicles in open-field and horticultural crops increases, safe navigation systems that detect and localise human workers in compliance with – yet to be developed - safety standards are expected to become crucial for agricultural robotic vehicle adoption and deployment.

781 **Acknowledgements**

We would like to thank the anonymous reviewers for their constructive comments. This work was funded by NIFA-USDA Award 2013-67021-21073 and NIFA-USDA Hatch Multi-State Grant 1001069.

785

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874

875 **Fig. 1** - The UWB localisation system consists of: 1) Utility vehicle, 2) Four vehicle radio beacons, 3)
876 Mobile radio beacon, 4) Mobile RTK GPS, 5) Vehicle RTK GPS, and 6) Total Station.

877 **Fig. 2** - Radio unit A measures and reports the distance (red dotted line) between the center points of
878 antennas A and B.

879 **Fig. 3** - Coordinate frames of the vehicle, radio beacons, GPSv, GPSm, and TS.

880 **Fig. 4** - The illustration of four ranges from vehicle beacons to the mobile beacon.

881 **Fig. 5** - Static test design in open space; black dots represent the locations of the static test points.

882 **Fig. 6** - Image from the pear tree orchard used for localization experiments.

883 **Fig. 7** - Static test design in orchard environment; black dots represent the locations of the static test
884 points.

885 **Fig. 8** - Dynamic test paths in: (a) open space, and (b) in an orchard.

886 **Fig. 9** - Open-space static test: positions measured with TS and GPSm and estimated via trilateration
887 in a specific test. Diamonds represent TS measurements; dots represent GPSm measurements; squares
888 represent the average trilateration estimate for each position.

889

890 **Fig. 10** - Theoretical ratio $ABSE_x/ABSE_y$ (Eq. 10) calculated over a $24 \times 24 \text{ m}^2$ square region
891 centered at the vehicle. Dots represent actual locations of measurements. Each pixel value encodes
892 whether the ratio $ABSE_x/ABSE_y$ is greater, less or equal to one. Diagonals and circle around vehicle
893 are loci of points where the ratio is equal to one. $ABSE_y < ABSE_x$ inside the cone-shaped regions
894 aligned with the y-axis; $ABSE_x < ABSE_y$ inside the cone-shaped regions aligned with x-axis.

895

Fig. 11 - DRMS and R95 metrics as functions of distance in open-space static tests.

896

Fig. 12 - (a) $ABSE_x$ and (b) $ABSE_y$ metrics plotted as a function of distance in open-space
static tests.

897

898 **Fig. 13** - Spatial distributions of theoretical error variances in open-space static tests: (a) $\text{var}(x_r)/\sigma^2$
899 and (b) $\text{var}(y_r)/\sigma^2$. $ABSE_x$ and $ABSE_y$ are proportional to the respective variances.

900

901 **Fig. 14** - Example path during open-space dynamic tests. Dots and squares represent GPSm

902 measurements and trilateration estimates respectively.

903

904 **Fig. 15** - Open-space dynamic tests: Horizontal distance error histogram and its fitted cumulative
905 probability density function for all points (units in cm).

Fig. 16 - DRMS and R95 metrics as functions of distance in open-space dynamic tests.

906 **Fig. 17** - Measured and trilaterated positions in the orchard static test during a specific test. Diamonds
907 represent TS measurements; dots represent GPSm measurements; squares represent the average
908 trilateration estimate for each position.

Fig. 18 - DRMS and R95 metrics as functions of distance in orchard static tests.

909 **Fig. 19** - Points on a sample path during dynamic testing in the orchard without body interference.
910 Dots and squares represent GPSm measurements and trilateration estimates respectively.

911

912 **Fig. 20** - Points on a sample path during dynamic testing in the orchard with full-LOS and body
913 interference. Dots and squares represent GPSm measurements and trilateration estimates respectively.